

# Environmental Technology Verification

## Test Report of Mobile Source Emissions Control Devices

Clean Diesel Technologies Fuel-Borne Catalyst  
with CleanAir System's Diesel Oxidation Catalyst

Prepared by

Southwest Research Institute



Research Triangle Institute



Under a Cooperative Agreement with  
U.S. Environmental Protection Agency



THE ENVIRONMENTAL TECHNOLOGY VERIFICATION  
PROGRAM



## ETV Joint Verification Statement

<b>TECHNOLOGY TYPE:</b>	<b>MOBILE DIESEL ENGINE AIR POLLUTION CONTROL</b>
<b>APPLICATION:</b>	<b>CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN HIGHWAY USE BY DIESEL OXIDATION CATALYSTS</b>
<b>TECHNOLOGY NAME:</b>	<b>CLEAN DIESEL TECHNOLOGIES, INC. FUEL-BORNE CATALYST WITH CLEANAIR SYSTEM'S DIESEL OXIDATION CATALYST</b>
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups, which consist of buyers, vendor organizations, permittees, and other interested parties; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Air Pollution Control Technology Verification Center (APCTVC), one of six centers under the ETV Program, is operated by Research Triangle Institute (RTI), in cooperation with EPA's National Risk Management Research Laboratory. The APCTVC has evaluated the performance of an emissions control system consisting of a fuel-borne catalyst for mobile diesel engines used with a diesel oxidation catalyst muffler.

## ETV TEST DESCRIPTION

All tests were performed in accordance with the *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, PM Filters, and Engine Modification Technologies for Highway and Nonroad Use Diesel Engines* and the *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Clean Diesel Technologies, Inc. 0.5Pt/7.5Ce Catalyst & CleanAir DOC*. These documents are written in accordance with the applicable generic verification protocol and include requirements for quality management, quality assurance, procedures for product selection, auditing of the test laboratories, and test reporting format.

The mobile diesel engine air pollution control technology was tested at Southwest Research Institute. The performance verified was the percentage emission reduction achieved by the technology for particulate matter (PM), nitrogen oxides (NO<sub>x</sub>), hydrocarbons (HC), and carbon monoxide (CO) relative to the performance of the same baseline engine without the technology in place. Operating conditions were documented and ancillary performance measurements were also made. A summary description of the ETV test is provided in Table 1.

**Table 1. Summary Description of the ETV Test**

Test type	Highway Transient Federal Test Procedure (FTP), heavy-duty cycle
Engine family	LCE0505FAC5
Engine make–model year	Cummins Engine Company–1990
Service class	On-highway, heavy duty diesel engine
Engine rated power	206 kW (275 bhp) @ 2,000 rpm
Engine displacement	8.3 L
Technology	Clean Diesel Technologies’ fuel-borne catalyst with CleanAir System’s Diesel Oxidation Catalyst
Technology description	A platinum/cerium fuel-borne catalyst (0.5Pt/7.5Ce ppm) in ultralow-sulfur diesel (ULSD) fuel combined with a diesel oxidation catalyst (Model CPD0950)
Test cycle or mode description	One cold-start and three hot-start tests according to FTP test
Test fuel description	EPA standard low-sulfur and ultralow-sulfur No. 2 diesel fuels per 40 CFR Part 86.1313
Critical measurements	PM, NO <sub>x</sub> , HC, and CO
Ancillary measurements	NO, NO <sub>2</sub> , CO <sub>2</sub> , exhaust back-pressure, exhaust temperature, and fuel consumption

## VERIFIED TECHNOLOGY DESCRIPTION

This verification statement is applicable to Clean Diesel Technologies' platinum/cerium fuel-borne catalyst (FBC) at 0.5 ppm platinum and 7.5 ppm cerium (0.5Pt/7.5Ce ppm)  $\pm$  20% in commercial ULSD fuel (meeting the EPA specifications for 2007 at less than 15 ppm maximum sulfur content) with a lightly catalyzed diesel oxidation catalyst (DOC) manufactured by CleanAir Systems (Model CPD0950). It is applicable to engines fueled by ultralow-sulfur (15 ppm or less) diesel fuel.

This verification statement describes the performance of the tested technology on the diesel engine and fuels identified in Table 1.

## VERIFICATION OF PERFORMANCE

The Clean Diesel Technologies fuel-borne catalyst used with CleanAir System's Diesel Oxidation Catalyst achieved the reduction in tailpipe emissions shown in Table 2 compared to baseline operation with low-sulfur diesel (LSD) fuel.

**Table 2. Verified Emissions Reductions for System Consisting of Clean Diesel Technologies fuel-borne catalyst with CleanAir Systems's Diesel Oxidation Catalyst**

Device type <sup>a</sup>	Fuel		Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
	Baseline	Controlled	PM <sup>b</sup>	NO <sub>x</sub>	HC	CO	PM <sup>b</sup>	NO <sub>x</sub>	HC	CO
Degreened	LSD	FBC & ULSD	53	7.4	59	64	49-58	5.8-9.1	56-62	60-69
Aged	LSD	FBC & ULSD	48	2.8	37	54	44-53	1.7-3.9	30-45	50-58

<sup>a</sup> Degreened and Aged are defined in the generic verification protocol.

<sup>b</sup> The verified PM emissions reduction combines reductions related to the control technology and the change in fuel sulfur level.

For the purposes of determining the status of the technology in regard to EPA's voluntary diesel retrofit program, the prospective user is encouraged to contact EPA's Office of Transportation and Air Quality (OTAQ) or visit the retrofit program web site at <http://www.epa.gov/otaq/retrofit/>.

The APCTVC QA Officer has reviewed the test results and quality control data and has concluded that the data quality objectives given in the generic verification protocol and test/QA plan have been attained. EPA and APCTVC quality assurance staff have conducted technical assessments at the test laboratory and of the data handling. These confirm that the ETV tests were conducted in accordance with the EPA-approved test/QA plan.

This verification statement verifies the emissions characteristics of the *Clean Diesel Technologies fuel-borne catalyst used with CleanAir System's Diesel Oxidation Catalyst* for the stated application. Extrapolation outside that range should be done with caution and an understanding of the scientific principles that control the performance of the technologies. This verification focused on emissions. Potential technology users may obtain other types of performance information from the manufacturer.

In accordance with the generic verification protocol, this verification statement is valid, commencing on the date below, indefinitely for application of *Clean Diesel Technologies fuel-borne catalyst used with CleanAir System's diesel oxidation catalyst* within the range of applicability of the statement.

Original signed by L. A. Mulkey      2/6/04

Lee A. Mulkey      Date  
Acting Director  
National Risk Management Research  
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Original signed by A. R. Trenholm      2/5/04

Andrew R. Trenholm      Date  
Director  
Air Pollution Control Technology  
Verification Center

# **Environmental Technology Verification Report**

## **Mobile Source Retrofit Air Pollution Control Devices**

**Clean Diesel Technologies' Fuel-borne Catalyst  
with CleanAir System's Diesel Oxidation Catalyst**

Prepared by

Research Triangle Institute  
Southwest Research Institute

EPA Cooperative Agreement No. CR829434-01-1

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## **Notice**

This document was prepared by Research Triangle Institute (RTI) and its subcontractor Southwest Research Institute (SwRI), with partial funding from Cooperative Agreement No. CR829434-01-1 with the U.S. Environmental Protection Agency (EPA). The document has been submitted to RTI/EPA's peer and administrative reviews and has been approved for publication. Mention of corporation names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products.

## Foreword

The Environmental Technology Verification (ETV) Program, established by the U.S. Environmental Protection Agency (EPA), is designed to accelerate the development and commercialization of new or improved technologies through third-party verification and reporting of performance. The goal of the ETV Program is to verify the performance of commercially ready environmental technologies through the evaluation of objective and quality-assured data so that potential purchasers and permittees are provided with an independent and credible assessment of the technology that they are buying or permitting.

The Air Pollution Control Technology Verification Center is part of the EPA's ETV Program and is operated as a partnership between Research Triangle Institute (RTI) and EPA. The Center verifies the performance of commercially ready air pollution control technologies. Verification tests use approved protocols and verified performance is reported in verification statements signed by EPA and RTI officials. RTI contracts with Southwest Research Institute (SwRI) to perform verification tests on engine emission control technologies.

Retrofit air pollution control devices used to control emissions from mobile diesel engines are among the technologies evaluated by the APCTVC. The APCTVC developed (and EPA approved) the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* to provide guidance on the verification testing of specific products that are designed to control emissions from diesel engines.

The following report reviews the performance of the Clean Diesel Technologies' platinum/cerium fuel-borne catalyst used with CleanAir System's Diesel Oxidation Catalyst (Model CPDo950). ETV testing of this technology was conducted during July 2003 at SwRI. All testing was performed in accordance with an approved test/QA plan that implements the requirements of the generic verification protocol at the test laboratory.



## **Availability of Report**

Copies of this verification report are available from

- Research Triangle Institute  
Engineering and Technology Division  
P.O. Box 12194  
Research Triangle Park, NC 27709-2194
- U.S. Environmental Protection Agency  
Air Pollution Prevention and Control Division (E343-02)  
109 T. W. Alexander Drive  
Research Triangle Park, NC 27711

Web sites:     <http://www.epa.gov/etv/verifications/verification-index.html> (electronic copy)  
                  <http://www.epa.gov/ncepihom/>

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## Acronyms/Abbreviations

°F	degrees Fahrenheit	NO <sub>2</sub>	nitrogen dioxide
°C	degrees Celsius	NO <sub>x</sub>	nitrogen oxide
APCTVC	Air Pollution Control Technology Verification Center	NDIR	nondispersive infrared
		OTAQ	Office of Transportation and Air Quality
bhp	brake horsepower	Pa	pascal(s)
bhp-hr	brake horsepower-hour	PM	particulate matter
BSFC	brake specific fuel consumption	ppm	parts per million by volume
cm	centimeter(s)	QA	quality assurance
CFR	Code of Federal Regulations	QC	quality control
CO	carbon monoxide	rpm	revolutions per minute
CO <sub>2</sub>	carbon dioxide	RTI	Research Triangle Institute
DOC	diesel oxidation catalyst	SOP	standard operating procedure
EPA	US Environmental Protection Agency	SwRI	Southwest Research Institute
ETV	Environmental Technology Verification	TPM	total particulate matter
FTP	Federal Test Procedure	ULSD	ultralow-sulfur diesel
ft	foot (feet)		
g	gram(s)		
HC	hydrocarbon(s)		
HD	heavy duty		
HFID	heated flame ionization detector		
in.	inch(es)		
in. Hg	inch(es) mercury		
kW	kilowatt(s)		
kWh	kilowatt hour(s)		
kPa	kilopascal(s)		
L	liter(s)		
Lpm	liters per minute		
lb	pound(s)		
lb-ft	pound foot (feet)		
LSD	low-sulfur diesel		
m	meter(s)		
min.	minute(s)		
mm	millimeter(s)		
N	newton(s)		
N-m	newton-meter		
NO	nitrogen oxide		

## **Acknowledgments**

The authors acknowledge the support of all of those who helped plan and conduct the verification activities. In particular, we would like to thank Theodore Brna, EPA's Project Manager, and Paul Groff, EPA's Quality Assurance Manager, both of EPA's National Risk Management Research Laboratory in Research Triangle Park, NC. We would also like to acknowledge the assistance and participation of all the Clean Diesel Technologies, Inc. personnel who supported the test effort.

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## **Section 1.0 Introduction**

This report reviews the performance of the Clean Diesel Technologies platinum/cerium fuel-borne catalyst used with CleanAir System's Diesel Oxidation Catalyst (Model CPD0950). Environmental Technology Verification (ETV) testing of this technology was conducted during a series of tests in July 2003 by Southwest Research Institute (SwRI) under contract with the Air Pollution Control Technology Verification Center (APCTVC). The objective of the APCTVC and the ETV Program is to verify, with high data quality, the performance of air pollution control technologies. Control of air emissions from diesel engines is within the scope of the APCTVC. An APCTVC program area was designed by Research Triangle Institute (RTI) and a technical panel of experts to evaluate the performance of diesel exhaust catalysts, particulate filters, and engine modification control technologies for mobile diesel engines. Based on the activities of this technical panel, the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*<sup>1</sup> was developed. This protocol was chosen as the best guide to verify the immediate performance effects of Clean Diesel Technologies' technology versus a protocol developed for fuel modifications. The verified technology incorporates both a catalyst added to the fuel and a device (the diesel oxidation catalyst). The specific test/quality assurance plan addendum for the ETV test of the technology submitted by Clean Diesel Technologies, Inc. was developed and approved on June 10, 2003.<sup>2</sup> The goal of the test was to measure the emissions control performance of the technology system and its emissions reduction relative to an uncontrolled engine.

A description of the Clean Diesel Technologies, Inc. fuel-borne catalyst and Diesel Oxidation Catalyst is presented in Section 2. Section 3 documents the procedures and methods used for the test and the conditions over which the test was conducted. The results of the test are summarized and discussed in Section 4, and references are presented in Section 5.

This report contains only summary information and data as well as the verification statement. Complete documentation of the test results is provided in a separate test report<sup>3</sup> and audit of data quality report.<sup>4</sup> These reports include the raw test data from product testing and supplemental testing, equipment calibration results, and quality assurance (QA) and quality control (QC) activities and results. Complete documentation of QA/QC activities and results, raw test data, and equipment calibration results are retained in Southwest Research Institute's files for seven years.

## Section 2.0

### Description of Products

The APCTVC conducted verification testing for Clean Diesel Technologies' system as described below (descriptions were provided by Clean Diesel Technologies). The system consisted of Clean Diesel Technologies' platinum/cerium fuel-borne catalyst (FBC) at 0.5 ppm ( $\pm 20\%$ ) platinum and 7.5 ppm ( $\pm 20\%$ ) cerium (0.5Pt/7.5Ce ppm) in commercial ultralow sulfur diesel fuel (ULSD) (meeting the EPA specifications for 2007 at less than 15 ppm maximum sulfur content) with a lightly catalyzed diesel oxidation catalyst (DOC) manufactured by Clean Air Systems (Model CPD0950). The technology was provided directly to the APCTVC's test organization, Southwest Research Institute, as:

- sufficient CDT Platinum Plus® platinum/cerium fuel-borne catalyst (FBC) to prepare about 200 gallons of ULSD ETV test fuel,
- one degreened CleanAIR Systems DOC (serial number 570070), with documented degreening history, and
- one aged CleanAIR Systems DOC (serial number 569790), with documented aging history.

The degreened DOC was operated for a total of 72 hours on Platinum Plus® FBC-treated ULSD. This included 56 hours of operation over repetitive Federal Test Procedure (FTP) cycles on a 1990 7.6 liter (L) DT 466 engine at SwRI prior to the verification test and 16 hours of operation on the test engine as part of the conditioning (repetitive transient cycle operation) for the verification test. The aged DOC was operated in commercial service for 1,000 hours on a 1992 Cummins L-10 equipped refuse truck as part of a California Air Resources Board (CARB) sponsored demonstration program with Waste Management in Long Beach, California. The aged DOC was installed in the field on 10/19/02 and was removed and shipped to SwRI on 4/29/03. Fuel in the CARB field program was ECD-1 ULSD treated at 0.5 ppm Pt/7.5 ppm Ce using an automatic FBC injection system mounted at the fuel dispensing pump. Both the degreened and aged DOC's were identical lightly catalyzed 24 x 15 cm (9.5 x 6 in.) ceramic substrates manufactured by Clean Air Systems of New Mexico.

All verification testing was conducted on a 1990 Cummins 8.3 L diesel engine fueled by conventional No. 2 diesel fuel for the baseline test and ULSD containing the FBC for the control system tests. Each DOC was mounted 1.5 to 1.8 m (5 to 6 ft) from the outlet of the turbocharger. Figure 1 shows the aged DOC mounted in the exhaust system in Test Cell 4.



**Figure 1. Aged DOC in Test Cell 4.**

### Section 3.0

#### Test Documentation

The ETV testing took place during July 2003 at Southwest Research Institute under contract to the APCTVC. Testing was performed in accordance with:

- *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*,<sup>1</sup>
- *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*,<sup>5</sup> and
- *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Clean Diesel Technologies, Inc. 0.5Pt/7.5Ce Catalyst & CleanAir DOC*.<sup>2</sup>

The applicant had reviewed the generic verification protocol and had an opportunity to review the test/QA plan prior to testing.

#### 3.1 Engine Description

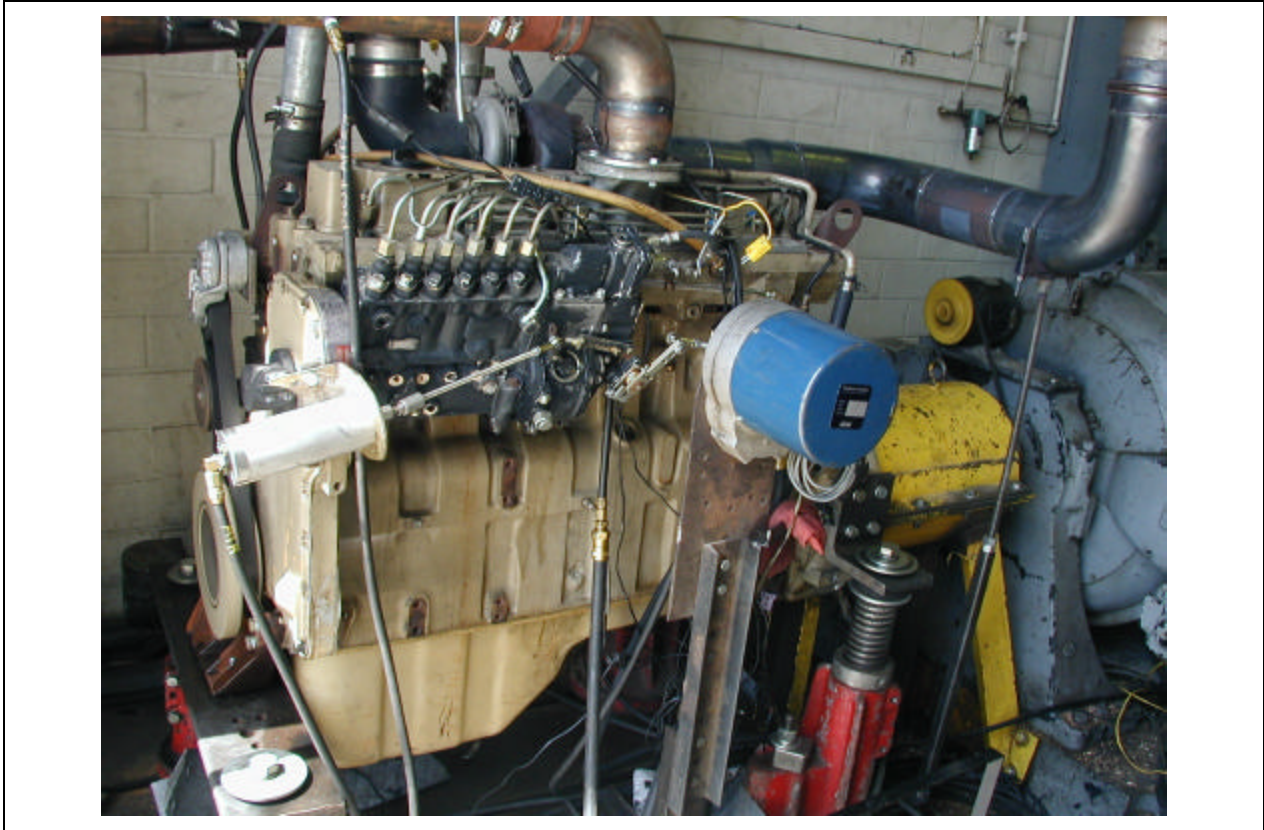
The ETV testing was performed on an in-line, six-cylinder, 8.3 L, 1990 model year, Cummins Engine Company, heavy-duty on-highway diesel engine. The engine was rated for 205 kW (275 bhp) at 2,000 rpm. It was turbocharged and used a laboratory water-to-air heat exchanger for a charge air intercooler. The engine was owned by SwRI and has been used in a number of test programs at SwRI.

Table 1 provides the engine identification details. Figure 2 shows the engine mounted in SwRI's test cell.

**Table 1. Engine Identification Information**

Engine serial number	44535723, CPL-1262
Date of manufacture	October 1990
Make	Cummins Engine Company, Inc.
Model year	1990 (certified to 1991 certification levels)
Model	C 8.3-275
Engine displacement and configuration	8.3 L, in-line 6
Service class	On-highway, heavy-duty (HD) diesel engine
EPA engine family identification	LCE0505FAC5
Rated power	205 kW (275 bhp) at 2,000 rpm
Rated torque	1100 N-m (800 lb-ft) at 1,300 rpm
Certified emission control system	Mechanical control
Aspiration	Turbocharged, air-to-air intercooled
Fuel system	Direct injection, mechanically controlled unit injectors





**Figure 2. 1990 Cummins 8.3L heavy-duty diesel engine mounted in engine Test Cell 4.**

### **3.2 Engine Fuel Description**

Two different diesel fuels were used during this verification test: a conventional No. 2 low-sulfur diesel (LSD) fuel with a sulfur level of 380 ppm and a No. 2 ULSD fuel treated with a FBC and having a sulfur level of 11 ppm. The LSD fuel meets EPA's current diesel fuel specifications given in 40 CFR § 86.1313-98, Table N98-2.<sup>6</sup> Selected fuel properties from SwRI's independent analyses are summarized for both fuels in Table 2. The ULSD that was FBC-treated is commercially available in California and met emissions equivalency to CARB ULSD. The ULSD deviated from the CFR diesel fuel specifications for the 10% boiling point and the minimum level of aromatics.

### **3.3 Summary of Emissions Measurement Procedures**

The ETV tests consisted of baseline uncontrolled tests and tests with the control system installed. The baseline engine was tested on conventional LSD fuel. The installed degreened and aged DOCs were tested with the FBC-treated ULSD. The engine and DOCs were conditioned using the FBC-treated ULSD before the official tests with one cold- and three hot-start transient cycles were conducted in accordance with the test/QA plan.<sup>5</sup> The standard HD Transient Federal Test Procedure<sup>7</sup> (FTP) for exhaust emissions testing was performed. Individual exhaust gas and particulate matter (PM) samples were taken for each cycle.

**Table 2. Selected Fuel Properties and Specifications**

Item	Code of Federal Regulations (CFR) Specification <sup>a</sup>				Test Fuel	
	ASTM	Type-2D	LSD EM-4895-F	FBC-treated ULSD EM-4920-F		
Cetane number	D613	40–50	48.0	53.4		
Cetane index	D976	40–50	48.5	50.0		
Distillation range:						
Initial boiling point, °C (°F)	D86	171–204 (340–400)	178 (352)	173 (344)		
10% Point, °C (°F)	D86	204–238 (400–460)	208 (406)	197 (386)		
50% Point, °C (°F)	D86	243–282 (470–540)	258 (497)	253 (488)		
90% Point, °C (°F)	D86	293–332 (560–630)	308 (586)	325 (617)		
End point, °C (°F)	D86	321–366 (610–690)	337 (639)	357 (675)		
Gravity (American Petroleum Institute)	D287	32–37	36.9	38.5		
Specific gravity		–	0.8402			
Total sulfur, ppm	D2622	(300–500) <sup>b</sup> (7–15) <sup>c</sup>	380	11		
Hydrocarbon composition:						
Aromatics (minimum), %	D1319	27	29.2	23.3		
Paraffins, naphthenes, and Olefins, %	D1319	<sup>d</sup>	70.8	76.7		
Flash point (minimum), °C (°F)	D93	54 (130)	71 (159)	68 (154)		
Viscosity, centistokes @ 40 °C	D445	2.0–3.2	2.4	2.4		

<sup>a</sup> Diesel fuel specification as in 40 CFR 86.1313-98(b)(2)<sup>6</sup> for the year 1998 and beyond and 40 CFR 86.1313-2007(b)(2)<sup>8</sup> for the year 2007 and beyond for heavy-duty diesel engines.

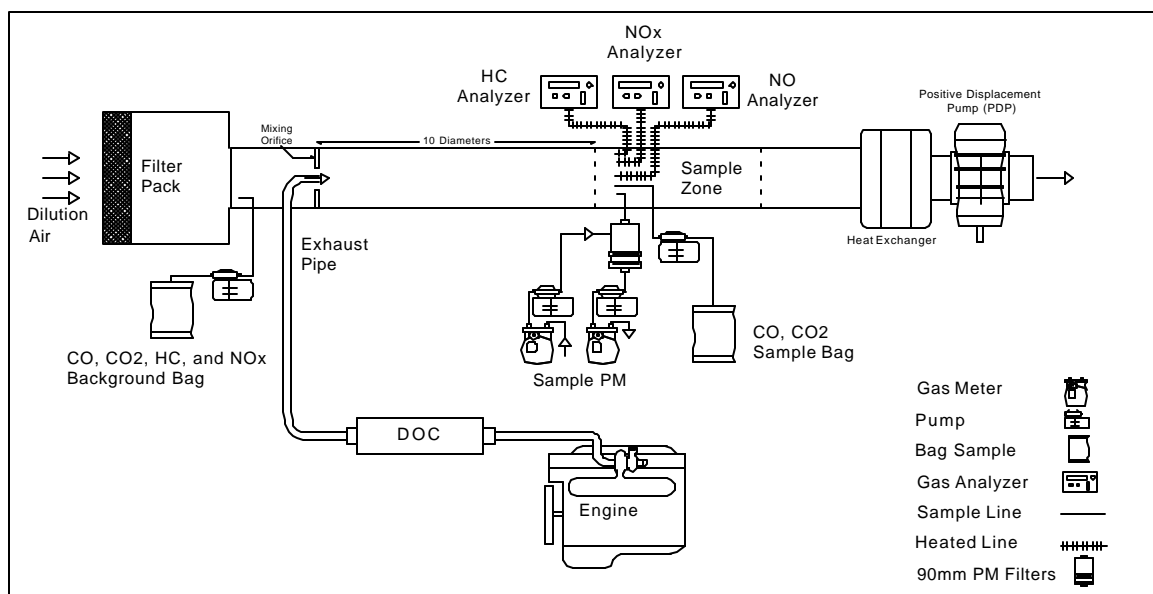
<sup>b</sup> 1998 sulfur range specification.

<sup>c</sup> 2007 sulfur range specification.

<sup>d</sup> Remainder of the hydrocarbons.

### ***Emissions Test Procedures***

Exhaust emissions were measured using HD Transient FTP<sup>7</sup> and the experimental setup shown in Figure 3. Dilute exhaust emissions measured during tests over the transient FTP operating conditions included total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), nitric oxide (NO), and exhaust PM. The CO and CO<sub>2</sub> levels were determined using nondispersive infrared (NDIR) instruments. Total HC were measured using continuous sampling techniques employing a heated flame ionization detector (HFID). The NO<sub>x</sub> and NO were measured continuously using two separate chemiluminescent analyzers, with NO<sub>2</sub> reported as the difference between NO<sub>x</sub> and NO.



**Figure 3. Constant volume sampler setup for emissions measurement.**

The exhaust PM level for each test was determined using dilute sampling techniques that collected PM on a pair of 90-mm diameter Pallflex T60A20 filter media used in series. The particulate filter pair unit was weighed together both before and after each test to establish exhaust PM emissions for the test.

### 3.4 Deviations from the Test/QA Plan

The initial cold-start transient test performed on July 1, 2003, did not meet the statistical limits for transient cycle operation. The results from this test were voided and no emission results were generated. A prep FTP test was conducted to insure that future tests would meet the statistical criteria for transient cycle operation. The planned baseline tests were run the following day.

On July 8, 2003 a computer failure was encountered during the second hot-start test with the aged DOC device. The two tests preceding the failure, a cold-start and the first hot-start, were valid tests; however the third test, the second hot-start, was voided and no results were generated. No attempt was made to run the third hot-start test that day. The computer function was restored and the entire one cold- and three hot-start test sequence was run the following day on the aged DOC test configuration. The latter complete sequence of data was used for the results in this report.

No transient torque map was run using the aged DOC. This torque map was scheduled for reference purposes only and its omission did not affect any emission results.

### 3.5 Documented Test Conditions

#### *Engine Performance*

Table 3 gives the observed engine performance while validating the power output of the Cummins engine for the baseline and the controlled configurations. The engine performance was very similar for both configurations with less than one percent difference in rated power and peak torque at the manufacturer's listed speeds of 2,000 rpm and 1,320 rpm respectively.

**Table 3. Engine Performance Data**

Fuel	Test Date	Test Number	Test Type	Rated Power <sup>a</sup> kW (bhp)	Peak Torque <sup>b</sup> lb- ft (N-m)
LSD	6/30/2003	PV1-4895	Baseline	203 (272)	1105 (815)
FBC-treated ULSD	7/3/2003	PV1-4920	Controlled	204 (274)	1105 (815)

<sup>a</sup>Engine power at rated speed of 2,000 rpm.

<sup>b</sup>Engine peak torque at rated speed of 1,320 rpm.

#### *Engine Exhaust Back-Pressure*

The engine back-pressure was set to 2.4 in. Hg (8.1 kPa) in accordance with the engine manufacturer specifications for the baseline configuration. The controlled configuration that included the degreened DOC or the aged DOC was run with the back-pressure set to 2.4 in. Hg (8.1 kPa).

#### *Engine Exhaust Temperature*

Temperature measurements were made in the exhaust system at the inlet and outlet of the DOC. The inlet temperature probe was located within the inlet subassembly of the DOC and the outlet temperature probe was located six inches downstream of the outlet subassembly in the exhaust pipe. Typical temperatures averaged over the transient test cycle were 212 °C (413 °F) at the DOC inlet and 228 °C (443 °F) at the DOC outlet. The temperature at the device inlet exceeded 225 °C more that 35 percent of the test duration.

#### *Fuel Consumption*

Table 4 presents the brake specific fuel consumption (BSFC) for all baseline and control configurations.

**Table 4. Brake Specific Fuel Consumption**

Test Number	Test Type	Test Date	BSFC, lb/bhp-hr	BSFC, kg/kWh	Weighted BSFC, lb/bhp-hr	Weighted BSFC, kg/kWh
Baseline with LSD fuel						
70203-C1	Cold-start	07/02/03	0.406	0.247		
70203-H1	Hot-start	07/02/03	0.396	0.241	0.397	0.240
70203-H2	Hot-start	07/02/03	0.397	0.242	0.398	0.241
70203-H3	Hot-start	07/02/03	0.398	0.242	0.399	0.241
Mean		07/02/03			0.398	0.241
Degreened DOC with FBC-treated ULSD fuel						
70703-C1	Cold-start	07/07/03	0.406	0.247		
70703-H1	Hot-start	07/07/03	0.391	0.238	0.393	0.238
70703-H3	Hot-start	07/07/03	0.390	0.237	0.392	0.237
70703-H4	Hot-start	07/07/03	0.388	0.236	0.391	0.236
Mean		07/07/03			0.392	0.237
Aged DOC with FBC-treated ULSD fuel						
70903-C1	Cold-start	07/09/03	0.411	0.250		
70903-H1	Hot-start	07/09/03	0.399	0.243	0.401	0.242
70903-H2	Hot-start	07/09/03	0.391	0.238	0.394	0.238
70903-H3	Hot-start	07/09/03	0.399	0.242	0.401	0.242
Mean		07/09/03			0.399	0.241

## Section 4.0

### Summary and Discussion of Emission Results

The baseline and controlled emissions data are summarized in Table 5. The emissions were measured at each test point for HC, CO, NO<sub>x</sub>, and PM. Table 5 also provides data on speciation of the NO<sub>x</sub> emissions, CO<sub>2</sub> emissions, and work. For each pollutant, hot-start test combination, the transient composite-weighted emissions per work (bhp-hr) were then calculated following the fractional calculation for highway engines as follows.

$$(E_{COMP})_m = \frac{1/7 \bullet E_{COLD} + 6/7 \bullet (E_{HOT})_m}{1/7 \bullet W_{COLD} + 6/7 \bullet (W_{HOT})_m} \quad (1)$$

where:

$$\begin{aligned} m &= 1, 2, \text{ or } 3 \text{ hot-start tests} \\ E_{COMP} &= \text{composite emissions rate, g/kWh (g/bhp-hr)} \\ E_{COLD} &= \text{cold-start mass emissions level, g} \\ E_{HOT} &= \text{hot-start mass emissions level, g} \\ W_{COLD} &= \text{cold-start brake horsepower-hour, kWh (bhp-hr)} \\ W_{HOT} &= \text{hot-start brake horsepower-hour, kWh (bhp-hr)} \end{aligned}$$

These composite-weighted emissions rates are shown in Tables 6 and 7 and were used to calculate the mean and standard deviations for the baseline and controlled emissions rates. These data were in turn used to calculate mean emissions reductions and 95 percent confidence limits. These calculations are based on the generic verification protocol<sup>1</sup> and test/QA plan.<sup>5</sup>

Table 8 summarizes the composite weighted emission values and Table 9 the verified emissions reductions and their 95 percent confidence limits.

**Table 5. Emissions Test Data**

Test Number	Test Type	Test Date	Exhaust PM	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>a</sup>	NO <sub>2</sub> / NO <sub>x</sub> , %	HC	CO	CO <sub>2</sub>	Work, KWh (bhp-hr)
			g					g			
Baseline with LSD fuel											
70203-C1	Cold-start	07/02/03	5.53	93.8	75.7	18.1	19.3	8.75	21.1	11.2	14.4 (19.3)
70203-H1	Hot-start	07/02/03	3.43	92.3	75.8	16.5	17.9	7.31	14.3	10.9	14.4 (19.3)
70203-H2	Hot-start	07/02/03	3.34	92.0	75.0	17.0	18.5	7.10	14.2	11.0	14.3 (19.2)
70203-H3	Hot-start	07/02/03	3.27	91.1	74.6	16.5	18.1	7.12	13.8	11.0	14.3 (19.2)
Degreened DOC with FBC-treated ULSD fuel											
70703-C1	Cold-start	07/07/03	2.53	85.5	77.4	8.15	9.54	3.83	9.56	11.0	14.1 (18.8)
70703-H1	Hot-start	07/07/03	1.57	84.9	76.4	8.46	9.97	2.88	5.00	10.7	14.2 (19.0)
70703-H3	Hot-start	07/07/03	1.57	82.3	74.3	8.04	9.77	2.91	4.41	10.5	14.1 (18.8)
70703-H4	Hot-start	07/07/03	1.52	84.1	75.7	8.40	9.98	2.85	4.41	10.6	14.2 (19.1)
Aged DOC with FBC-treated ULSD fuel											
70903-C1	Cold-start	07/09/03	2.83	90.5	79.0	11.5	12.7	6.01	11.5	11.1	14.1 (18.9)
70903-H1	Hot-start	07/09/03	1.72	85.4	75.4	9.96	11.7	4.65	6.17	10.6	13.8 (18.5)
70903-H2	Hot-start	07/09/03	1.67	86.5	75.2	11.3	13.1	4.12	5.78	10.5	14.0 (18.8)
70903-H3	Hot-start	07/09/03	1.63	87.7	76.0	11.7	13.4	4.05	5.91	10.8	14.1 (18.9)

<sup>a</sup> NO<sub>2</sub> calculated as NO<sub>x</sub> - NO.

**Table 6. Composite Weighted Emissions Values (English units)**

Test Number	Test Type	Test Date	Exhaust PM	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>a</sup>	NO <sub>2</sub> / NO <sub>x</sub> , %	HC	CO	CO <sub>2</sub>
			g/bhp-hr					g/bhp-hr		
Baseline with LSD fuel										
70203-H1	Hot-start	07/02/03	0.194	4.80	3.93	0.867	18.1	0.390	0.792	570
70203-H2	Hot-start	07/02/03	0.190	4.80	3.91	0.891	18.6	0.382	0.789	572
70203-H3	Hot-start	07/02/03	0.187	4.76	3.89	0.868	18.3	0.383	0.770	572
Degreened DOC with FBC-treated ULSD fuel										
70703-H1	Hot-start	07/07/03	0.0897	4.47	4.03	0.443	9.90	0.159	0.297	564
70703-H3	Hot-start	07/07/03	0.0904	4.39	3.96	0.427	9.73	0.161	0.273	562
70703-H4	Hot-start	07/07/03	0.0874	4.42	3.98	0.439	9.92	0.157	0.270	560
Aged DOC with FBC-treated ULSD fuel										
70903-H1	Hot-start	07/09/03	0.101	4.65	4.10	0.549	11.8	0.261	0.374	574
70903-H2	Hot-start	07/09/03	0.0974	4.63	4.03	0.603	13.0	0.234	0.351	565
70903-H3	Hot-start	07/09/03	0.0956	4.67	4.05	0.620	13.3	0.229	0.355	574

<sup>a</sup> NO<sub>2</sub> calculated as NO<sub>x</sub> - NO.



**Table 7. Composite Weighted Emissions Values (metric units)**

Test Number	Test Type	Test Date	Exhaust PM	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>a</sup>	NO <sub>2</sub> / NO <sub>x</sub> , %	HC	CO	CO <sub>2</sub>
			g/kWh					g/kWh		
Baseline with LSD fuel										
70203-H1	Hot-start	07/02/03	0.259	6.40	5.24	1.16	18.1	0.520	1.06	760
70203-H2	Hot-start	07/02/03	0.253	6.40	5.21	1.19	18.6	0.509	1.05	763
70203-H3	Hot-start	07/02/03	0.249	6.35	5.19	1.16	18.3	0.511	1.03	763
Degreened DOC with FBC-treated ULSD fuel										
70703-H1	Hot-start	07/07/03	0.120	5.96	5.37	0.591	9.90	0.212	0.396	752
70703-H3	Hot-start	07/07/03	0.121	5.85	5.28	0.569	9.73	0.215	0.364	749
70703-H4	Hot-start	07/07/03	0.117	5.89	5.31	0.585	9.92	0.209	0.360	747
Aged DOC with FBC-treated ULSD fuel										
70903-H1	Hot-start	07/09/03	0.135	6.20	5.47	0.732	11.8	0.348	0.499	765
70903-H2	Hot-start	07/09/03	0.130	6.17	5.37	0.804	13.0	0.312	0.468	753
70903-H3	Hot-start	07/09/03	0.127	6.23	5.40	0.827	13.3	0.305	0.473	765

<sup>a</sup> NO<sub>2</sub> calculated as NO<sub>x</sub> - NO.

**Table 8. Summary of Verification Test Emission Values**

Device type	Fuel	Mean Composite Weighted Emission Value, g/kWh (g/bhp-hr)				
		PM	NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
Baseline	LSD	0.253 (0.190)	6.37 (4.78)	0.513 (0.385)	1.05 (0.784)	761 (571)
Degreened	FBC-treated ULSD	0.119 (0.0892)	5.91 (4.43)	0.212 (0.159)	0.373 (0.280)	749 (562)
Aged	FBC-treated ULSD	0.131 (0.0981)	6.20 (4.65)	0.321 (0.241)	0.480 (0.360)	761 (571)

**Table 9. Summary of Verification Test Emission Reductions**

Device type	Fuel		Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
	Baseline	Controlled	PM <sup>a</sup>	NO <sub>x</sub>	HC	CO	PM <sup>a</sup>	NO <sub>x</sub>	HC	CO
Degreened	LSD	FBC-treated ULSD	53	7.4	59	64	49-58	5.8-9.1	56-62	60-69
Aged	LSD	FBC-treated ULSD	48	2.8	37	54	44-53	1.7-3.9	30-45	50-58

<sup>a</sup> The verified PM emissions reduction combines reductions related to the control technology and the change in fuel sulfur level.

#### 4.1 Quality Assurance

The environmental technology verification of the DOC muffler with FBC-treated ULSD fuel for heavy-duty diesel engines was performed in accordance with the test/QA plan.<sup>5</sup> An audit of data quality included the review of equipment, personnel qualifications, procedures, record keeping, data validation, analysis, and reporting. Preliminary, in-process, and final inspections, and a review of 10 percent of the data showed that the requirements stipulated in the test/QA plan<sup>5</sup> were achieved. The APCTVC's quality manager reviewed the test results and the quality control data and concluded that the data quality objectives given in the generic verification protocol were attained. EPA and RTI quality assurance staff conducted audits of SwRI's technical and quality systems in April 2002 and found no deficiencies that would adversely impact the quality of results. The equipment was appropriate for the verification testing, and it was operating satisfactorily. SwRI's technical staff were well qualified to perform the testing and conducted themselves in a professional manner.

## **Section 5.0**

### **References**

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3. Southwest Research Institute. Environmental Technology Verification of CDT's Fuel-borne Catalyst with CleanAir System's Diesel Oxidation Catalyst Mufflers for Use with Heavy-Duty Diesel Engines. San Antonio, TX, August 2003.
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5. Research Triangle Institute. Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines. Research Triangle Park, NC, April 2002, [http://www.epa.gov/etv/pdfs/vp/05\\_tp\\_diesel.pdf](http://www.epa.gov/etv/pdfs/vp/05_tp_diesel.pdf).
6. Fuel specifications, 40 CFR § 86.1313-98, Table N98-2 (updated July 2001).
7. 40 CFR § 86, Subpart N, as of July 1, 1999, <http://www.epa.gov/epahome/cfr40.htm>.
8. Fuel specifications, 40 CFR § 86.1313-2007, Table N07-2 (updated January 2001).